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A simple framework to quantitatively describe monthly precipitation and temperature climatology

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1 **A simple framework to quantitatively describe monthly precipitation**
2 **and temperature climatology**

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10

11 **Keywords:** climate; precipitation; temperature; similarity index; analytical
12 framework.

13

14 **Key points:**

15 - Global monthly precipitation and temperature climatology is described by a simple
16 sinusoidal pattern

17 - Analytical framework with five indices describes mean monthly climate time-series

18 - The framework can provide a quantitative basis for climate descriptions among

19 different sciences

20 Abstract

21 Climate descriptors and classifications are vital for ordering past, current and future
22 climatic conditions. Yet, these parsimonious descriptors of climatic conditions only
23 capture specific aspects of this climate signal, and lose all other information available
24 in the observations. As a result, climate descriptions are often not physically
25 insightful when they are applied in other studies. In this study, we show that a
26 sinusoidal function with an annual period can adequately describe the vast majority of
27 monthly precipitation and temperature climates around the world. This finding allows
28 us to synthesize intra-annual monthly precipitation and temperature climatology using
29 5 indices that are easy to interpret. The indices describe (i) the mean precipitation rate
30 (\bar{P}), (ii) the mean temperature (\bar{T}), (iii) the seasonal precipitation amplitude (δ_P), (iv)
31 the seasonal temperature amplitude (Δ_T), and (v) the phase difference between the
32 precipitation and temperature regimes (s_d). The combination of the 5 indices
33 describes the relative time series of precipitation and temperature climatology, in
34 contrast to earlier proposed similarity indices that only capture specific aspects of
35 these time series. We demonstrate how the framework can reproduce many earlier
36 proposed indices and classifications, and provide an example how the framework can
37 be used to classify regions. We argue that the framework provides comprehensive
38 insight into global climatology and can function as a quantitative conceptual basis for
39 climate descriptions among different sciences.

40

41 1. Introduction

42 Climate is defined as the generally prevailing weather conditions of a region, often
43 averaged over a 30-year period [WMO, 1989]. Climate descriptors and classifications
44 summarize characteristics of the climate signal and thereby they help to bring

45 structure and order to the diversity of climates around the world. Similarity indices
46 and classifications can order climate based on a single climatic characteristic (e.g.
47 precipitation amount), or classify climate based on the combination of several
48 climatic characteristics (e.g. precipitation amount and a temperature condition). Such
49 descriptions help to delineate regions with specific climatic conditions. Because
50 climate influences many factors, these descriptions are vital for understanding,
51 explaining and predicting how regions differ in ecologic, water cycle, landscape and
52 anthropogenic conditions.

53

54 Energy availability (temperature, net radiation, potential evaporation) and moisture
55 availability (precipitation) form the core of many widely adopted climate descriptors
56 and classifications [e.g., Köppen, 1936; Thornthwaite, 1931, 1948; Holdridge, 1967;
57 Trewartha, 1968; Budyko, 1974; Alley, 1984; Kottek et al., 2006; Peel et al., 2007].
58 The mean intra-annual pattern of energy availability and moisture availability has a
59 distinct imprint on a diverse range of factors, such as vegetation type [Köppen, 1936;
60 Holdridge, 1967; Trewartha, 1968; Stephenson, 1992; Gonzalez et al., 2010],
61 ecosystem productivity [Harris et al., 2000; Parton et al., 2012; Robinson et al., 2013],
62 agricultural production [Kurukulasuriya et al., 2003; Deryng et al., 2011], carbon
63 storage and release [Heimann & Reichstein, 2008], dissolved nutrient retention
64 dynamics [Ye et al., 2012], evaporation rates [Wolock & McCabe, 1999; Berghuijs et
65 al., 2014a], soil moisture storage [Milly, 1994; Seneviratne et al., 2010], snowpack
66 and glacial dynamics [Woods, 2009; Bartholomew et al., 2010], droughts [Reynolds
67 et al., 1999; Mishra & Singh, 2010; van Loon et al., 2014], river flow [Thornthwaite,
68 1931; Budyko, 1974; Petersen et al., 2012; Berghuijs et al., 2014b], aquatic
69 communities [Poff et al., 1997; Kattwinkel et al., 2011], animal activity [Richardson,

1990; Mills et al., 1995; van Doorn et al., 2010], wildfire activity [Westerling et al., 2006; Slocum et al., 2010], geomorphology [Etheredge et al., 2004; Nigel & Rughooputh, 2010], human well-being [Dasgupta et al., 2001], infectious diseases [Koelle et al., 2005], heart-failure [Stewart et al., 2002] and labor capacity [Dunne et al., 2013].

Climate descriptors and classifications provide different ways to describe the climatic similarities and differences among places. Providing an overview of climate classification systems is beyond the scope of this study; we refer to Oliver [2005] for a list and description of several climate classification schemes. However, we identify that all classifications and descriptors have in common that they rely on indices that describe only a specific condition of the climate signal (e.g. the number of days a certain temperature is exceeded), which is sufficient to distinguish members of one class from another class. A descriptor is generally chosen because it is strongly linked to another character of interest (e.g. vegetation growing season). Reproduction of the mean monthly climate signal is not possible using solely these classification indices as all other information about the observed climate is not captured within the index. The fact that the indices lose a lot of information makes it difficult to use one set of climate descriptors or a specific classification across different scientific disciplines, as descriptors do not provide enough information to derive other characteristics of the climate. This lack of universal descriptors hinders climate descriptors from being effectively used to support advocated synthesis between different fields of study [Rodriguez-Iturbe, 2000; Harte, 2002; Weart, 2013]. The loss of information is also an important indicator that there is currently no comprehensive concise descriptor of what monthly climate patterns are actually occurring globally, as only some specific

95 conditions can be inferred from current climate classifications. Additionally, the loss
96 of information prevents climate descriptors from being used to force mechanistic
97 models. Falsifiable models are vital for testing physical understanding of
98 interdependencies between climate and related factors.

99

100 If the monthly precipitation and temperature climatology consist of patterns that can
101 be described with parsimonious mathematical functions, there is potential to develop
102 descriptors of the monthly climate signal that maintain most of the information that is
103 present in the observations, while using only a few numeric descriptors to characterize
104 the climate. If the indices maintain enough information to describe the within-year
105 patterns of the climate signal, these indices can be used to derive any characteristic of
106 the climate that is a function of the intra-annual precipitation and temperature signal.
107 This would significantly improve our ability to conceptualize what monthly climate
108 patterns are occurring globally, and allow a similar reference framework among
109 different sciences and studies.

110

111 The primary factors affecting local temperature are a location's latitude, and altitude
112 [Fleming et al., 1988]. The latitude strongly influences the seasonality of the mean
113 monthly temperature and the mean temperature. The altitude mainly affects the mean
114 temperature. Other controls on temperature include cloud cover variations [Tsushima
115 & Manabe, 2001], land-cover [Feddema et al., 2005], soil-moisture [Seneviratne et
116 al., 2010], distance from the ocean [Geerts, 2003], air and ocean currents [Jones et al.,
117 2007], among other factors. Yet, due to the dominance of the seasonal change of the
118 inclination of the sun, we hypothesize it is plausible to use a sinusoidal function with
119 an annual period to describe the monthly temperature climatology of locations. The

120 use of a sinusoidal function to model seasonal temperature variation has been applied
121 in the contiguous US [Woods, 2009; Berghuijs et al., 2014b], is used for educational
122 purposes, or to model diurnal temperature variation [Snyder, 1985]. These studies did
123 not quantify to what degree a simple sinusoidal function is able to describe the mean
124 monthly temperature signal, nor was it applied on a global scale.

125

126 Several studies also used a sinusoidal function with an annual period to describe mean
127 monthly precipitation. This description for precipitation is used regionally in the
128 United States [Milly 1994; Woods, 2009; Berghuijs et al., 2014b], in parts of
129 Australia [Potter et al., 2005; Hickel & Zhang, 2006] and globally [Blöschl et al.,
130 2013]. Similar to temperature, these studies did not quantify to what degree a
131 sinusoidal function can describe the mean monthly precipitation signal. Additionally
132 the sinusoidal functions have been defined such that the seasonal precipitation
133 amplitude had an upper bound, with the consequence that climates containing several
134 months without precipitation could not be accurately described. This description
135 dismisses the possibility of accurately describing bimodal seasonal cycles around the
136 tropics, but is chosen to maintain parsimony.

137

138 In this study we examine to what degree observations of the monthly climate signal of
139 precipitation and temperature can be described by a sinusoidal function with an
140 annual period, and no upper bound to the precipitation seasonality. This can
141 potentially reveal to what degree there is a distinct pattern in the global monthly
142 climate signal, which allows synthesizing most of the monthly precipitation and
143 temperature climatology using 5 indices that are straightforward to interpret
144 physically. Subsequently we demonstrate how the framework can reproduce other

145 characteristics of the climate signal and can be used to classify distinct climates.
146 Finally, we discuss how this quantitative conceptualization can improve our
147 understanding of global climatology and can provide a basis for climate similarity
148 schemes among different sciences.

149

150 **2. Methods**

151 **2.1. Data**

152 We use monthly precipitation and surface temperature values for the period 1980-
153 2009 from the Modern-Era Retrospective Analysis for Research and Applications
154 improved set of land surface hydrological fields [MERRA-Land; Reichle et al., 2011].
155 The data have a 2/3-degrees longitude by 1/2-degrees latitude resolution. A
156 quantitative comparison with the Global Precipitation Climatology Project (GPCP)
157 [Huffman et al., 2009] indicates that MERRA-Land mean annual precipitation rates
158 are lower than GPCP in parts of South America and central Africa, and higher than
159 GPCP in Southeast Asia and along parts of the South American and African coasts
160 [Reichle et al., 2011]. Although research has indicated that small biases of
161 precipitation rates can occur regionally compared to other precipitation products,
162 MERRA-Land reproduces precipitation well over land-surface [Reichle et al., 2011],
163 especially the seasonal cycle [Kim et al., 2014]. We assess precipitation and
164 temperature characteristics for all grid-cells where more than 50% of the cell area is
165 classified as land.

166

167 **2.2. Sinusoidal functions**

168 The sinusoidal functions used to describe monthly precipitation and temperature are
169 defined in Equation 1 and Equation 2:

$$P(t) = \bar{P} [1 + \delta_P \sin(2\pi(t - s_P)/\tau)] \quad (1)$$

$$T(t) = \bar{T} + \Delta_T [\sin(2\pi(t - s_T)/\tau)] \quad (2)$$

where P is the precipitation rate (mm/month), T is the temperature ($^{\circ}\text{C}$), t is the time (year), \bar{P} is the mean precipitation rate (mm/month), \bar{T} is the mean temperature ($^{\circ}\text{C}$), δ_P is the dimensionless seasonal precipitation amplitude (-), Δ_T is the seasonal temperature amplitude ($^{\circ}\text{C}$), τ is the duration of the seasonal cycle, set at 1 year, and the phase shifts (year) of temperature (s_T) and precipitation (s_P) are time offsets from a reference date, in this study set as Jan 1st. Δ_T and δ_P can range from zero to infinity. s_T and s_P can range from zero to one. Figure 1a and 1b illustrates an example climate according to the descriptions in Equation 1 and Equation 2.

In contrast to earlier studies [Milly, 1994; Potter et al., 2005; Hickel & Zhang, 2006; Woods, 2009; Blöschl et al., 2013; Berghuijs et al., 2014b], we remove the restriction that the maximum seasonality of precipitation has an upper bound of $\delta_P = 1$. This change allows description of climates where there are multiple months without precipitation. In the case that δ_P exceeds 1, equation 1 is generalized with a correction factor (C_r) to ensure that the average precipitation rate remains \bar{P} :

$$P(t) = \max(0, \bar{P} \cdot [1 + C_r + \delta_P \sin(2\pi(t - s_P)/\tau)]) \quad (3)$$

where,

$$C_r = -0.001 \cdot \delta_P^4 + 0.026 \cdot \delta_P^3 - 0.245 \cdot \delta_P^2 + 0.2432 \cdot \delta_P - 0.038 \quad (4)$$

Figure 1c gives an overview of several precipitation regimes for a range of seasonal precipitation amplitudes. Figure 1d displays how the correction factor (C_r) varies as a function of the seasonal precipitation amplitude (δ_P). The time-averaged value of $P(t)$

can deviate from \bar{P} because C_T is numerically approximated (see Supplementary Material, Figure S1).

194

To reduce the number of indices needed to characterize the climate, we introduce the phase difference between the precipitation and temperature regime (s_d). s_d expresses to what degree the precipitation and temperature patterns are in phase, by quantifying how much earlier temperature peaks compared to the precipitation regime:

$$s_d = s_P - s_T, \text{ for } |s_P - s_T| \leq 0.5 \quad (5a)$$

$$s_d = -1 + (s_P - s_T), \text{ for } (s_P - s_T) > 0.5 \quad (5b)$$

$$s_d = 1 + (s_P - s_T), \text{ for } (s_P - s_T) < -0.5 \quad (5c)$$

s_d can range from -0.5 (completely out of phase, P peaks before T), to 0 (completely in phase), to 0.5 (completely out of phase, P peaks after T). For the climate displayed in Figure 1a,b s_d equals -0.40 [year].

205

The 5 indices needed to characterize the relative time series of mean monthly precipitation and temperature now are: (i) the mean precipitation rate (\bar{P}), (ii) the mean temperature (\bar{T}), (iii) the seasonal precipitation amplitude (δ_P), (iv) the seasonal temperature amplitude (Δ_T), and (v) the phase difference between the precipitation and temperature regimes (s_d).

211

2.3. Derivation of other climate characteristics

The 5 indices can be used to derive any climate characteristic that is a function of the mean within-year pattern of precipitation and temperature. Derived characteristics

can, for example, consist solely of temperature characteristics such as the duration that the temperature is above a certain threshold temperature (T_c):

$$t_T = \frac{-2 \sin^{-1} \left(\frac{T_c - \bar{T}}{\Delta_T} \right) + \pi}{2\pi} \quad (6)$$

Similarly, the duration that the seasonal precipitation is above a certain threshold precipitation (P_c) can be approximated by:

$$t_P = \frac{-2 \sin^{-1} \left(\frac{P_c - \bar{P}}{\bar{P} \cdot \delta_P} \right) + \pi}{2\pi}, \text{ for } \delta_P \leq 1 \quad (7)$$

These equations can be used to derive climate characteristics such as the number of frost days [Easterling, 2002], number of tropical days [Nastos & Matzarakis, 2008], number of dry months [Trejo & Dirzo, 2002], number of wet months [Trejo & Dirzo, 2002]. Similar expressions can be derived for indices such as precipitation seasonality [Walsh & Lawler, 1981], precipitation concentration index [Oliver, 1980], degree-day factor [Hock, 2003], and cooling degree month [Sturm et al., 1995].

Temperature and precipitation characteristics can be combined to express how much precipitation falls while a certain temperature condition is met. Examples are annual snowfall, the fraction of precipitation that falls as snow [Woods, 2009; Berghuijs et al. 2014b], and the precipitation in the growing season [Ylhäisi et al., 2010]. Woods [2009] showed how the fraction of precipitation falling below a certain temperature threshold (T_0) is calculated as follows:

$$f_s = f_s(\bar{T}^*, \delta_P^*) = \frac{1}{2} - \frac{\sin^{-1}(\bar{T}^*)}{\pi} - \frac{\delta_P^*}{\pi} \sqrt{1 - \bar{T}^*}, \text{ for } \delta_P \leq 1 \quad (8a)$$

where,

$$\delta_P^* = \delta_P \cdot \text{sgn}(\Delta_T) \cdot \cos(2\pi \cdot s_d) \quad (8b)$$

$$\overline{T^*} = \frac{\overline{T} - T_0}{|\Delta_T|} \quad (8c)$$

Because the indices describe the character of widely used sinusoidal functions, analytical solutions can be derived for other precipitation, temperature or combined characteristics. The widely adopted classifications of [Köppen, 1936; Thornthwaite, 1931, 1948; Holdridge, 1967; Trewartha, 1968; Budyko, 1974; Peel et al., 2007] can also be reproduced, but this requires more laborious expressions, sometimes including calculation of potential evaporation based on mean monthly temperature [e.g. Hamon, 1961].

242

2.4. Calibration and evaluation

To test the adequacy of the sinusoidal function with an annual period for the description of the precipitation and temperature climate we define two objective functions that express the goodness of fit for the temperature and precipitation approximations:

$$X_T = \sum_{t=1}^{12} \frac{|T(t) - T_t|}{12} \quad (9)$$

$$X_p = \sum_{t=1}^{12} \frac{|P(t) - P_t|}{\overline{P}} \quad (10)$$

where X_p expresses the mean monthly precipitation error normalized by the average precipitation rate (-). When the error, X_p , is 0 the sinusoidal function is a perfect fit to the observed precipitation value P_t .

253

The value of X_p expresses to what degree the monthly precipitation deviates relative to the mean monthly value observed at that location. X_T expresses the mean monthly temperature error ($^{\circ}\text{C}$), which is the mean absolute error in the temperature approximation (T_t is the observed temperature). The coefficients of Equation 1 and 2

are obtained by the Simplex search method [Nelder & Mead, 1965] of MATLAB's
fminsearch to minimize X_T and X_P [Lacouture & Cousineau, 2008]. For both the
optimizations \bar{P} and \bar{T} are fixed according to the long-term average observed values;
only the seasonal amplitude and phase shift are calibrated. The objective functions are
chosen because they have the same units as the observed and described signal, and
they can be interpreted without information on the variance in the observations.

264

265 3. Results

We first provide an overview of the global monthly climatology according to the
description by the sinusoidal functions. Subsequently we evaluate in more detail the
appropriateness of the sinusoidal function to describe the monthly precipitation and
temperature climatology. Finally we assess the correspondence of characteristics of
the climate derived from the 5 indices and characteristics of the climate directly
derived from the observations.

272

273 3.1. Global monthly climatology

Figure 2 displays the global occurrence of the mean temperature (\bar{T}), the seasonal
amplitude of temperature (Δ_T), the phase shift of the temperature regime compared to
January 1st (s_T), and the temperature error (X_T) in approximating the observed data by
a sinusoidal function. The mean temperature for the assessed grid cells varies between
-28.1 and 37.1°C. The seasonal temperature amplitude also varies strongly across the
grid cells with a maximum Δ_T of 32.5°C. The approximation of the monthly
temperature signal gives an average temperature error (X_T) of 0.85°C, with a standard
deviation of 0.44°C. This error is relatively small compared to the mean seasonal
amplitude of temperature, Δ_T , of 12.8°C (median = 12.8°C). The regions where the

temperature error is large coincide with the regions where the seasonal temperature amplitude (Δ_T) is also large or with regions with a highly seasonal precipitation regime. In the areas with a seasonal precipitation regime the seasonal change in soil moisture can be a strong control on the surface energy balance, thereby affecting the intra-annual temperature pattern; this is one possible cause of the larger errors.

Figure 3 displays the global occurrence of the mean precipitation rate (\bar{P}), the seasonal precipitation amplitude (δ_p), the phase shift (s_p), and the precipitation error (X_p). The precipitation rate ranges from a minimum of 4 mm/y, to a maximum of 10561 mm/y. The global mean precipitation rate is 706 mm/y (median = 501 mm/y). The seasonality of the precipitation varies regionally; δ_p has an average value of 0.80 (-) (median = 0.63), but can locally be as high as 4.7 (-). The approximation of the seasonal precipitation signal, on average, leads to a mean absolute error of the monthly precipitation of $X_p = 0.17$ (-), with a standard deviation of 0.12. With a mean seasonality of precipitation (δ_p) equal to 0.80 this suggests that, on average, the within-year seasonality of precipitation is largely captured by the sinusoidal description.

Figure 4 displays the phase difference between the precipitation and temperature regimes (s_d). This phase difference is for most regions relatively close to 0 indicating that precipitation amounts are the highest during the warmer months at the given location. In some regions of all the continents the precipitation amounts are highest during the cool season.

306

3.2. Assessment of errors

308 To improve understanding of the ability of the sinusoidal function to describe the
309 precipitation regime we highlight how well the description works as a function of
310 precipitation characteristics, and how the errors vary between regions.

311

312 The regional differences in errors indicate that the sinusoidal function is not always an
313 informative description of the monthly precipitation regime as the approximation can
314 show relatively high error values (see map of X_P in Fig 3). The percentage of grid
315 cells where X_P is larger than 0.30 (-) is 12.6%. Of these grid cells 69.0% are located
316 in dry regions with annual precipitation below 300 mm/y. The regions with very low
317 precipitation rates (<300 mm/y) sometimes have too few precipitation events to
318 identify a smooth seasonal pattern. Other regions where high precipitation errors are
319 observed are mostly in highly seasonal precipitation regimes ($\delta_p > 1.0$). Figure S2
320 (Supplementary Material) delineates the grid cells in discrete classes based on the X_P ,
321 δ_p , and \bar{P} values.

322

323 The grid cells where X_P is larger than 0.3 are only located in a limited number of
324 regions (See Figure S2). Reasons for these high X_P values vary regionally. Table S1
325 gives a point wise description per region that shows high ($X_P > 0.3$) values. These
326 descriptions indicate the regional reasons for the higher error value and should
327 improve understanding of the regional adequacy of the hypothesis that the monthly
328 precipitation pattern can be described with the sinusoidal function. The sinusoidal
329 approximation is not informative in regions with a bimodal rainfall pattern such as
330 southwestern United States and the Horn of Africa.

331

Figure 5 gives an overview of the measured and modeled temperature and precipitation regimes, to give qualitative understanding how well the approximations describe the observed regimes. For different ranges of precipitation seasonality we have selected individual grid-cells whose error value is the 25th percentile, median and 75th percentile for that category, in order to view seasonal regimes where the sinusoidal functions produce high, medium and low errors. For the temperature regimes the 75th percentile and better fits all have a very good correspondence between the sinusoidal function and the actual observations. Hence the sinusoidal functions also visually appear very suitable for describing the monthly temperature pattern. For the precipitation patterns the correspondence between the sinusoidal function and the actual observations is lower. Although we visually inspected the measurements of all grid cells, we were not able to identify a more suitable simple mathematical function to describe the measured precipitation regime in a similar parsimonious manner.

3.3. Comparison of framework and data-derived climate characteristics

We evaluate the ability of the framework to reproduce specific climatic characteristics. This gives an indication of the suitability of the framework to provide a common reference for studies that are interested in specific climate characteristics. We compare characteristics of the climate as assessed by the 5 similarity indices and characteristics of the climate directly derived from the data. The derived indices include temperature-based, precipitation-based and combined temperature and precipitation characteristics. The characteristics of the climate assessed, and their definitions are listed in Table 1. Given the large number of grid cells involved, the correspondence between the analytically derived and the data-derived values is

357 summarized by the slope of a linear regression (indication of accuracy), and the R^2 –
358 value of the linear regression (indication of precision). The analytically derived value
359 is used as the explanatory variable. The combination of the linear regression slope and
360 the R^2 -value expresses how all the information contained in these similarity indices
361 can be reproduced with the reference framework.

362

363 The slopes of the linear regression approach one for most climate indices, with R^2 –
364 values also approaching one (see Table 1). This indicates enough information is
365 captured within the framework to accurately and relatively precisely reproduce a
366 variety of widely used climate indices. Temperature indices (duration frost season,
367 duration growing season, cooling degree month) have the highest R^2 -value, which is
368 also expected considering the good fit between temperature observations and
369 descriptions. The R^2 -value for precipitation characteristics (dry period [Peel et al.
370 [2007], wet period [Peel et al., 2007] and precipitation seasonality [Walsh & Lawler,
371 1981]) decrease slightly, but slopes still are close to one with R^2 also close to one.
372 One variable to highlight is the precipitation seasonality index as defined by Walsh &
373 Lawer [1985]. The slope of the linear regression gives a value of 0.90 which confirms
374 that most of the precipitation variability is captured by the sinusoidal function. For
375 combined characteristics (fraction of precipitation falling as snowfall [Woods, 2009],
376 growing season precipitation [Ylhäisi et al., 2010], Holdridge aridity index
377 [Holdridge, 1969; Shen et al., 2011]) the performance decreases again, but still R^2 –
378 values are around 0.90 and the slope of the linear regression still approaches one. The
379 correspondence with the Köppen main class according to the definitions used in Peel
380 et al. [2007] gives a 99.81% correspondence between derived classes, indicating that
381 this widely used classification scheme can be reproduced as well.

382

383 **4. The framework as a classification tool**

384 The framework can be used as a classification tool to characterize or cluster climate
 385 based on the five indices using the notation: $[\bar{P}, \bar{T}, \delta_P, \Delta_T, s_d]$. An example grid-cell
 386 in New Zealand [43.5300°S, 172.6203°E] has the characteristics [662.9, 6.8, 0.30,
 387 6.86, -0.01]. When regions with comparable climates are defined, the single values
 388 can be replaced by the associated minimum and maximum value, e.g. [600/800, 5/10,
 389 0.1/0.4, 4/8, -0.25/0.25]. Another type of classification can make the different
 390 components dependent on another, e.g. $[(600+30\bar{T})/(800+30\bar{T}), 5/10, 0.1/0.4, 4/8, -$
 391 $0.25/0.25]$.

392

393 As an example, we classify the land surface into different climatic regions. The four
 394 indices $[\bar{P}, \bar{T}, \delta_P, \Delta_T]$ are divided into tertiles with an equal number of grid-cells per
 395 group; per index there is a group of low, medium and high values. The 5th index (s_d)
 396 is divided into a group of small and large phase differences, again with an equal
 397 number of grid-cells. Climate classes are constructed based on the combination of the
 398 above-mentioned groups, leading to $3^4 \cdot 2 = 162$ climate classes. However, not all
 399 combinations of groups occur, resulting in 120 classes with grid-cells assigned. Figure
 400 6 displays the class boundary conditions (bottom right), and the spatial distribution of
 401 classes with more than 250 grid-cells. Although the current example classification
 402 does not have a specific purpose beyond providing an example, the framework allows
 403 classifying climate groups quantitatively, while maintaining the qualitatively easy to
 404 interpret character (e.g. cold, wet, high rainfall seasonality, medium temperature
 405 seasonality, out of phase). Table S2 (Supplementary Material) provides an overview
 406 of all classes and the number of grid-cells assigned per class.

407

408 **5. Discussion**409 **5.1. Is the sinusoidal function suitable to describe monthly climatology?**

410 We aimed to develop descriptors of the intra-annual precipitation and temperature
411 climate that maintain most of the monthly information that is present in the observed
412 signal, while using a limited number of descriptors to characterize the climate. By
413 identifying that most of the climates around the world can be described by a
414 sinusoidal pattern with an annual period, both for monthly precipitation and
415 temperature, simple analytical functions appear to be very suitable for this purpose.
416 The most parsimonious description that still acknowledges intra-annual variation of
417 precipitation and temperature consist of 5 indices: here described by \bar{P} , \bar{T} , δ_P , Δ_T and
418 s_d . More parsimonious descriptors integrate these dimensions and therefore by
419 definition lose information.

420

421 The systematic comparison of the analytical model performance with the observed
422 data indicates regional differences in the adequacy of the sinusoidal function for
423 describing the observed monthly regimes. For the temperature climatology, Figure 5
424 shows that the seasonal pattern is well described by the sinusoidal function, as the
425 mean absolute error (X_T) is much smaller than the within-year variability of the
426 temperature regime (Δ_T). Considering that the climatic descriptors should be
427 parsimonious and easily understandable, we have not identified an opportunity to
428 improve on the sinusoidal description to describe the monthly temperature pattern,
429 while still maintaining the parsimony and simplicity of the current sinusoidal
430 description.

431

432 The goodness of fit (X_p) of the precipitation regimes indicates that the sinusoidal
433 function for most regions provides a reasonable approximate for the precipitation
434 regimes. High errors, with few exceptions, occur either in the very dry places ($P < 300$
435 mm/y), or in places with hyperseasonal precipitation ($\delta_p > 1$). The significant
436 percentage of grid cells with a hyper seasonal precipitation regime indicates that
437 previous characterizations with an upper bound of 1.0 for the seasonality [Milly,
438 1994; Potter et al., 2005; Hickel & Zhang, 2006; Woods, 2009; Blöschl et al., 2013;
439 Berghuijs et al., 2014b] are not suitable for characterizing the global monthly
440 precipitation climatology, though it can be applied in some regions.

441

442 For the precipitation pattern the error in the sinusoidal approximation can be
443 regionally relatively high, and there is more room for a refined mathematical
444 description, especially in regions with a clear bimodal monthly precipitation regime.
445 In dry regions the monthly precipitation rates are based on a limited number of
446 precipitation events, so there is often no smooth mean monthly pattern. Improvement
447 of the parsimonious precipitation description will consequently be very difficult for
448 regions with low precipitation rates. The data we used for the fitting of our framework
449 are interpolated, which may impact the performance of the framework. This may be
450 particularly important in arid data poor regions, where there is the possibility of poor
451 performance due to inaccurate data interpolation.

452

453 The balance between providing an appropriate and detailed description of the climate
454 and providing a simple parsimonious understandable description depends on the
455 purpose of the frameworks. Earlier studies used more detailed sinusoidal functions to

456 describe regional climatic gradients [Horn & Bryson, 1960], or suggested to
457 regionally change the period of the seasonal cycle to half a year [Milly, 1994].
458 Although such refinements may improve the correspondence of the analytical
459 function and the observed climate signal, they also require more indicators to describe
460 the climate and are physically less easy to interpret. The most detailed description of
461 monthly precipitation and temperature values, are the actual observed values.
462 However, description of this information requires two numbers for every month to
463 characterize the climate, and thus is inappropriate to characterize the climate in a
464 quickly understandable way when the climate of many different locations needs to be
465 characterized or compared.
466
467 Whether the errors introduced by the approximation are problematic completely
468 depends on the purpose the framework is used for. In context of studies that use other
469 climate indices or climate classes, the suitability of the mathematical approximation is
470 underpinned by the high correspondence between derived climate characteristics with
471 the framework and climate characteristics based on measurements. This indicates the
472 amount of information lost by summarizing the monthly climate with the 5-indices is
473 very small as the reproduction of other variables is well maintained. Comparison with
474 the precipitation seasonality index of Walsh & Lawler [1985] indicates that on
475 average most of the variability of mean intra-annual precipitation is captured within
476 the description. However, some information (the error) is lost and not available for
477 detailed assessments when only the 5 climate descriptors are used.
478
479 Evaluation of the descriptors of the monthly climate is only performed for grid-scale
480 precipitation and temperature, which does not take into account sub-grid variability.

Hence the hypothesis is not tested at sub-grid scales. Further testing and mapping for sub-grid variability is left for future work. Yet as the hypothesis originates from applications at local sites, it is not expected that at sub-grid scales the performance will change significantly. The proposed description is scale-independent in its application and hence a potentially useful way to characterize any place at any scale or to characterize the variability or mean of a single unit, at other than grid-scales (e.g. a river basin).

488

5.2. What insight can the similarity indices give?

By identifying that the mean monthly climatology in many parts of the world can be described by a sinusoidal pattern we simplified the mean climate signal into five dimensions, which has multiple uses, and limitations. A clear limitation of the framework is the loss of detail available in the observed signal, such as between year variability, short-term variability etc. A description of mean seasonal climate does not incorporate, but can be expanded by, descriptors that characterize precipitation characteristics such as storminess and inter-annual variability. The 5 indices are thus currently not adequate for forcing mechanistic models or studies that require detailed data (e.g. daily) of the temporal climate conditions. Additionally the error of precipitation and/or temperature can be too large to highlight climatic differences in regional studies that compare climatologically almost equivalent sites. Therefore the descriptors will not always be suitable for local assessments that require as much detailed information as possible. These limitations are intrinsic properties of any climate classification and climate descriptors.

504

505 The framework is rather intended as a tool to order global dominant features of
506 monthly precipitation and temperature climatology. Because our description provides
507 a good approximation to the time series of observed climatology, our framework can
508 provide a much more comprehensive understanding on what monthly climate patterns
509 are occurring globally compared to earlier parsimonious climate descriptors. This
510 more comprehensive way of describing monthly climatology has multiple distinct
511 advantages compared to the classifications and indices that describe only specific
512 characteristics of the monthly climatology but lose all other information obtained in
513 the observations.

514

515 The framework makes it conceptually much easier to describe the actual physical
516 gradients of monthly climatology between two places. The similarity indices we
517 propose all have a well-defined, unambiguously interpretable definition. Many
518 previous similarity indices and classifications [e.g., Köppen, 1936; Kottek et al.,
519 2006; Peel et al., 2007] are rather a combination of numerical indices where the
520 physical gradient between places cannot be expressed within a quantitative manner or
521 sometimes even conceptual manner. Expressing these physical gradients between
522 places in a conceptually easy manner is not only valuable for education purposes but
523 also can assist in exposing physical gradients that underpin differences and similarity
524 between places for research purposes.

525

526 Sanderson [1999] advocated for a novel classification of the world climates. “*Modern*
527 *textbooks continue to use the 100-year old Köppen classification of climates [Köppen,*
528 *1936], which is based on de Candolle’s vegetation groups, themselves based on the*
529 *five climatic zones of the ancient Greeks.*” The limited physical information contained

530 in the similarity indices systems remains a barrier to give insight into the climatic
531 similarity and differences between places. Additionally, because all classification
532 systems have their specific purpose (e.g. cluster vegetation similarity) it is difficult to
533 use the indices across different studies and sciences. For example, the limited
534 quantitative information on the intra-annual climate conditions that is contained in
535 Köppen's classification makes it unsuitable as a common reference framework for
536 many different studies. Because of the much smaller loss of information in our
537 framework and the ability to reproduce previous classifications we argue our
538 framework can generate a conceptual step forward in characterizing the within year
539 variations of the climate, where climatic differences between places are easily
540 expressed.

541
542 We argue that our framework can provide a quantitative conceptual basis for climate
543 descriptions among different sciences. Because the analysis of section 3.3 indicates
544 the approximated regimes can accurately reproduce other climate descriptors, the
545 framework can provide a holistic picture of the monthly precipitation and temperature
546 climatology. Goals of previous climate indices [e.g. Walsh & Lawler, 1985;
547 Easterling, 2002; Trejo & Dirzo, 2002; Nastos & Matzarakis, 2008] and
548 classifications have been to organize the climate such that specific climate-dependent
549 characteristics occur in a region [e.g. Köppen, 1936; Holdridge, 1967; Trewartha,
550 1968]. In contrast, our framework provides five climate dimensions that in a simple
551 manner can characterize under which monthly precipitation and temperature
552 climatology the case specific assessments occur. Many climate indices and climates
553 of classification schemes are derived from the mean intra-annual precipitation and
554 temperature pattern. Consequently, these indicators can all be expressed in terms of

555 the 5 proposed climate indices. The framework can thus provide a common reference
556 scheme to describe climatic conditions, and thereby better highlight climatic
557 similarity and differences between places.

558

559 Classification, the delineation of groups with similar characteristics, is always
560 purpose specific, except when there are discrete differences between the observed
561 items, such as classes in Linnaean taxonomy [Linnaeus, 1788], elements of the
562 periodic table [Mendeleev, 1869], and turbulent and laminar flow in fluid mechanics
563 [Belanger, 1828]. Our framework rather uses continuous numbers to describe the
564 character of climate where discrete classes are based on more purpose-specific
565 conditions. The 5-dimensions form a continuum in which we can only subdivide by
566 putting in artificial boundaries. We provided an example based on arbitrarily chosen
567 class boundaries, which classified the land surface into different climatic regions.
568 Although this classification does not have a specific purpose beyond providing an
569 example, it shows how the framework allows classifying climate groups
570 quantitatively, while maintaining a qualitatively easy to interpret character.

571

572 The fact that the full within-year climatology is described using the indices means that
573 the indices can force mechanistic models [e.g. Woods, 2003, 2009; Potter et al.,
574 2005]. This characteristic, combined with the notion that the indices can express the
575 climatic gradients between several places, make it potentially a powerful tool to
576 combine simple mechanistic and falsifiable models and large scale climate
577 classifications. Additionally, the framework may provide a useful tool to characterize
578 past or future climatic change or variations in a holistic, physically easily interpretable
579 way compared to using changes in the discrete Köppen climate classes [Rubel &

580 Kottek, 2010; Chen & Chen, 2013], changes in speed of change of Köppen climate
581 classes [Mahlstein et al., 2013], changes in precipitation concentration [Luis et al.,
582 2011], and changes in mean-annual climatology [Greve et al., 2014].

583

584 **6. Conclusions**

585 Climate is a key factor in many sciences and determines the diversity of many biotic
586 and abiotic factors around the world. Climate descriptors and climate classifications
587 are widely used tools to synthesize climatic conditions in a parsimonious manner and
588 are vital for understanding, ordering and describing the global climatic diversity. The
589 diversity of climates around the world makes it difficult to produce parsimonious
590 descriptors of climatic conditions that still maintain most of the information present in
591 the observed signal. Consequently, climate descriptors and classifications only
592 describe a specific aspect of the climate signal, or they have a qualitative character.
593 As a result, climate descriptions are often physically not very insightful when they are
594 applied in other sciences or studies.

595

596 In this study we showed that a sinusoidal function with an annual period can describe
597 most of the monthly precipitation and temperature patterns. The mean absolute
598 temperature error of the sinusoidal function is 0.85 (°C), which is an order of
599 magnitude smaller than the mean intra-annual variation of temperature. Similarly, the
600 mean monthly error of precipitation is on average below 0.18 [-]; high error values
601 mainly occur in regions with low precipitation rates or in regions with a very seasonal
602 precipitation regime.

603

604 This finding allows us to synthesize most of the monthly precipitation and
605 temperature patterns using 5 indices that are physically easy to interpret. The indices
606 describe (i) the mean precipitation rate (\bar{P}), (ii) the mean temperature (\bar{T}), (iii) the
607 seasonal precipitation amplitude (δ_P), (iv) the seasonal temperature amplitude (Δ_T),
608 and (v) the phase difference between the precipitation and temperature regime (s_d).
609 The combination of the 5 indices summarizes the relative time series of mean monthly
610 precipitation and temperature. Quantitative comparison of characteristics of the
611 climate as assessed by the 5 similarity indices and directly derived from the original
612 climatic data shows good correspondence. This indicates the framework is able to
613 give a holistic picture of climatic conditions, but also indicates its ability to provide a
614 common reference framework for studies that are interested in more specific climate
615 characteristics. As an example, we classify the land surface into different climatic
616 regions based on the five indices. Although this classification does not have a specific
617 purpose beyond providing an example, it shows how the framework allows
618 classifying climate groups quantitatively, while maintaining a qualitatively easy to
619 interpret character.

620

621 Hence the proposed framework provides a basis to summarize the global diversity of
622 monthly precipitation and temperature climatology within a 5-dimensional space.
623 This allows expressing the climatic diversity in a simple and understandable manner,
624 while the quantitative character of the monthly climate signal is maintained. Because
625 a wide range of climatic classification and similarity indices can be brought back to
626 the 5-dimensional space the framework can be used as a common reference scheme
627 among different sciences.

628

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884 distribution of classes. The phase shift s_d is delineated into two classes: high (H) and

- 885 low (L) values are merged into one group (L) because of the cyclic behavior of s_d .
- 886 Classes with less than 250 grid-cells are not presented.

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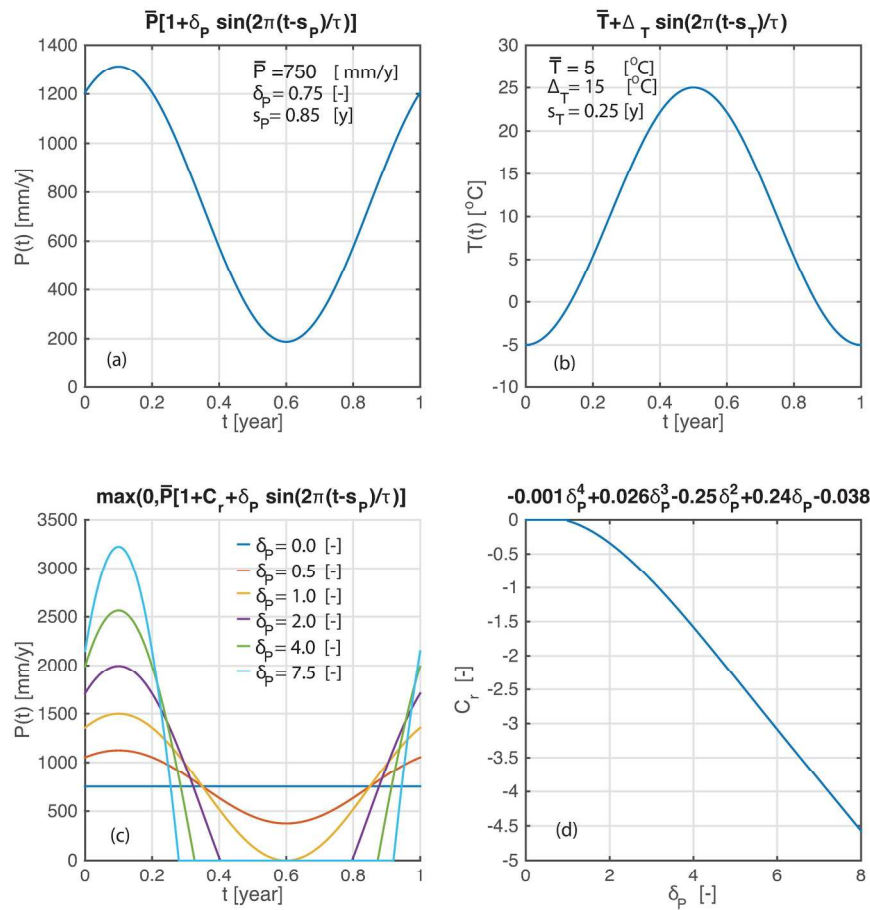


Figure1. Conceptual description of monthly climate according the framework; example of a precipitation regime (Fig. 1a), a temperature regime (Fig. 1b), several precipitation regimes for a range of seasonal precipitation amplitudes (Fig. 1c), and correction factor C_r as a function of the seasonal precipitation amplitude (δ_p) (Fig. 1d).
193x193mm (300 x 300 DPI)

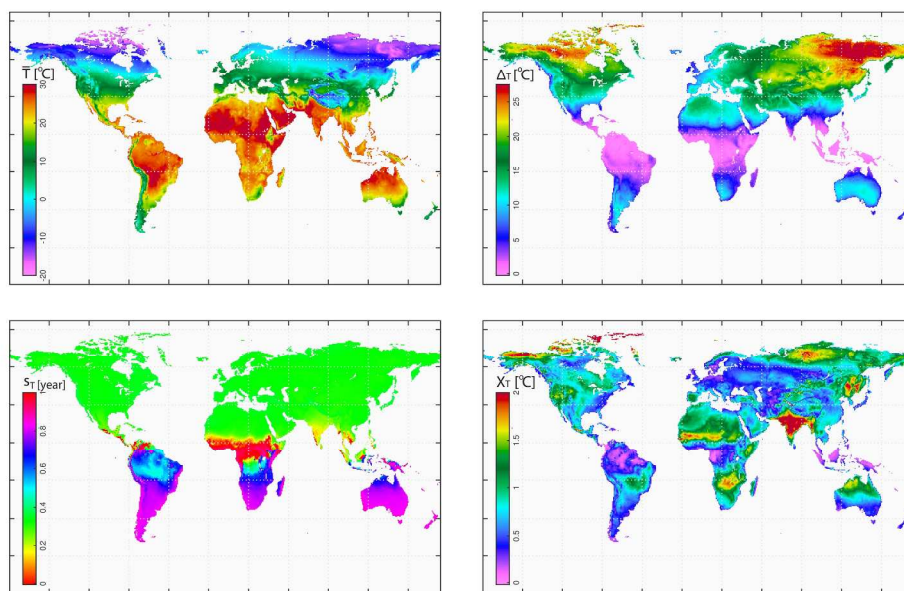


Figure 2. The mean temperature (T), the seasonal temperature amplitude (ΔT), the phase shift (s_T), and the monthly temperature error (X_T).
264x174mm (300 x 300 DPI)

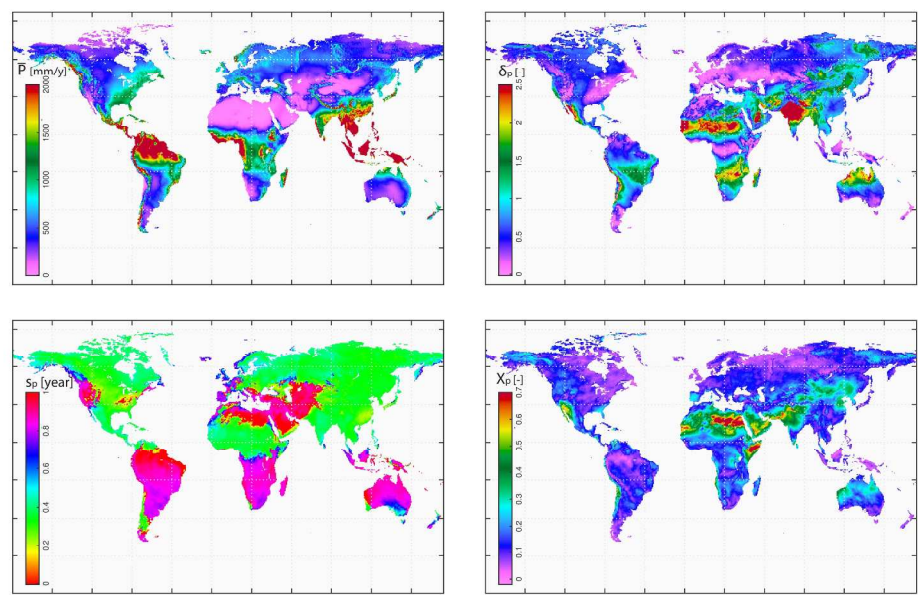


Figure 3: The mean precipitation rate (P), the dimensionless seasonal temperature amplitude (δ_P), the phase shift (s_P), and the monthly precipitation error (X_P).
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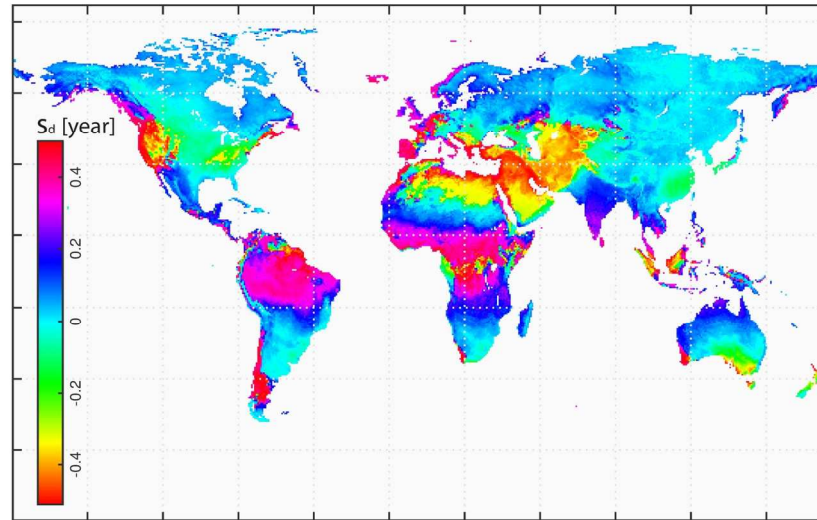


Figure 4. The phase difference between the precipitation and temperature regime (S_d).
141x94mm (300 x 300 DPI)

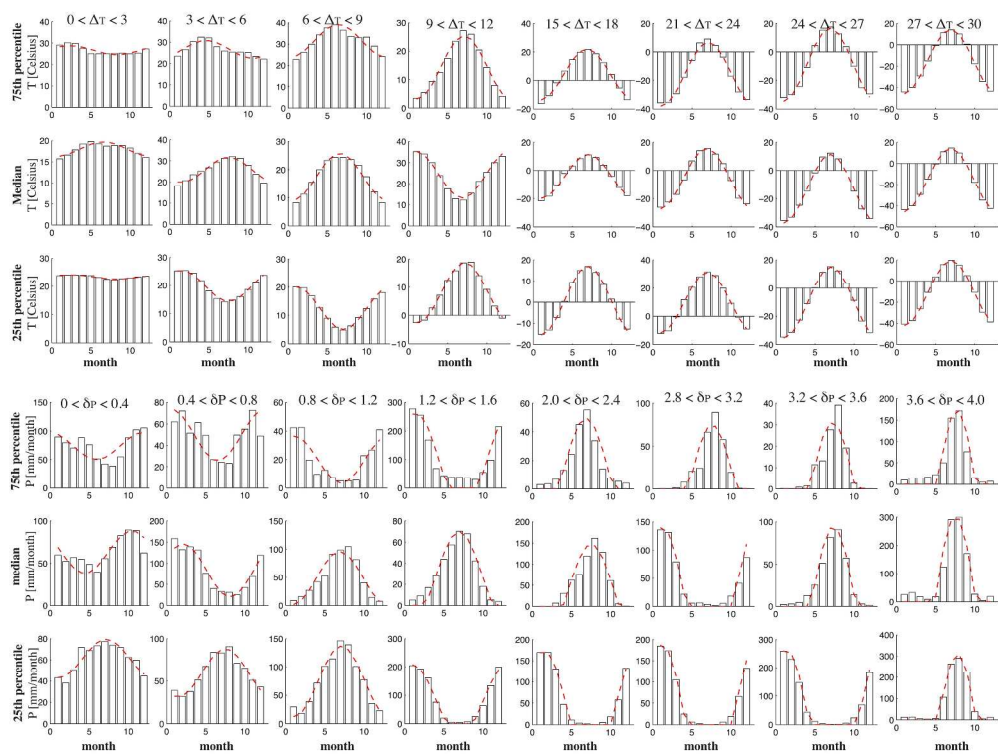


Figure 5. MERRA-Land observation (bar) and analytically approximated (dashed line) monthly temperature and precipitation climatology of the individual grid-cells that fall at 25th percentile, median, and 75th percentile values of different δ_p and ΔT intervals.
312x242mm (300 x 300 DPI)

Climate descriptor	Description	Definition	Slope linear regression	R ²
Duration frost season	Period that mean temperature is below freezing point [Easterling, 2002].	$\sum t(T(t)<0)/\sum t$	0.9970	0.9890
Duration growing season	Period that mean temperature is above a certain threshold, here set at 8 (°C).	$\sum t(T(t)>8)/\sum t$	1.0115	0.9899
Cooling degree month	Time-accumulated winter temperature exceeding a temperature threshold [Sturm et al., 1995].	$\sum (T_c - T(t)), \text{ if } T(t) < T_c$	0.9981	0.9999
Dry period	Period that the mean precipitation rate is lower than 60 (mm/month) [Peel et al., 2007].	$\sum t(P(t)<60)/\sum t$	1.0137	0.9592
Wet period	Period that the mean precipitation rate is higher than 60 (mm/month) [Peel et al., 2007].	$\sum t(P(t)>60)/\sum t$	0.9672	0.9688
Precipitation seasonality	Mean deviation of monthly precipitation compared to the mean annual precipitation [Walsh & Lawler, 1981].	$(\sum P(t) - P(t)/12)/(\sum P(t))$	0.9473	0.9610
Fraction of precipitation falling as snowfall	Precipitation falling as snowfall (as derived by a temperature threshold) divided by the total amount of precipitation [Woods, 2009].	$(\sum P(T(t)<1))/(\sum P)$	1.0463	0.8997
Growing season precipitation	Annual amount of precipitation falling when growing season conditions ($T > 8$ °C) [Ylhäisi et al., 2010].	$\sum P(T(t)>8)$	1.0367	0.9262
Holdridge aridity index	Climatic water availability in each part of the year, defined as the ratio of the temperature to the annual precipitation [Holdridge, 1969; Shen et al., 2011].	$(58.93 \sum T(t(T>0)))/P$	1.0121	0.9845
Köppen-Geiger main-class	Percentage of grid-cells that are assigned to the correct Köppen-class according to the definitions of Peel et al [2007].	See Table 1 in Peel et al [2007].	-	99.81%